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LITERATURE REVIEW AND EVALUATION OF THE EPA FOOD-CHAIN (KENAGA) NOMOGRAM, AN INSTRUMENT FOR ESTIMATING PESTICIDE RESIDUES ON PLANTS

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Abstract—The Kenaga nomogram is a simple device that was developed by the U.S. Environmental Protection Agency (EPA) in the early 1980s and is currently used to predict the maximum potential pesticide residue levels in the food chain of wildlife before pesticide registration. To evaluate the accuracy of this nomogram, predicted levels were compared to levels reported in the literature. Data (obtained from the UTAB database developed by the University of Oklahoma) demonstrated that day-0 levels predicted by the nomogram were often exceeded. Data from the UTAB database exceeded the nomogram predictions by the following percentages listed by crop: short range grass, 0; leafy crops, 3; long grass, 4; pods/seeds, 8; fruits, 19; and forage (legumes), 22. Minor modification of the nomogram is recommended. Recommended modifications would result in an elevation of the predicted residue levels for fruits and forage (legume) crops.

Keywords—Food chain Nomogram Pesticides Plant residue UTAB database

INTRODUCTION

Ecological risk assessment of the hazard posed by agrochemicals to wildlife requires consideration of both the toxicity of chemicals to wildlife and the exposure that birds and other animals receive in natural habitats [1,2]. The U.S. Environmental Protection Agency (EPA) initially estimates the ecological risk associated with pesticides by using a quotient method that divides the estimated level of environmental exposure by the concentration of a chemical required to elicit a biological response (usually lab data) [1]. Quotient values approaching or exceeding 1.0 indicate that a given chemical is more likely to have an adverse effect on wildlife in the environment.

Exposure levels (i.e., the quotient's numerator) are based in part on estimates of food-chain contamination often found through the use of a simple nomogram (Fig. 1) compiled by the EPA in the early 1980s. The nomogram [3] has been nicknamed the Kenaga nomogram by the EPA in recognition of the source of the data used to compile it [4]. The Kenaga nomogram is used to predict maximum residue level present on day 0 following different application rates of a chemical to one of six different categories of plants or plant parts.

The three basic features of the Kenaga nomogram—categories of plants and plant parts, maximum predicted residue levels, and linear dose–residue relationship—are drawn from a review article published by Hoerger and Kenaga in 1972 [4]. In preparing their review article, the authors reported they considered several hundred publications, but only included illustrative data in their review from the 22 papers they found with the highest levels of pesticide residues from spray application. Thus, Hoerger and Kenaga purposefully emphasized the most rigorous situations requiring toxicological evaluation of which they were aware at that time, and contended that it was highly unlikely for residue levels to exist above the upper-limit values reported in their publication.

The data taken from the Hoerger–Kenaga review and used by the EPA to develop the Kenaga nomogram pertain to 36 crops and 27 pesticides. However, 10 of the 27 pesticides considered by Hoerger and Kenaga in 1972 are now either banned or no longer registered in the United States (e.g., DDT, dieldrin, endrin, and aldrin). Also, many pesticides have been introduced. In light of these developments, there is a need to reexamine and possibly update the Kenaga nomogram.

This study reexamines the Kenaga nomogram using voluminous information compiled at the University of Oklahoma in the UTAB database [5,6]. Database information regarding both crops and pesticides has been used in this reexamination, which was guided by six questions:

1. Are the maximum predicted residue values correct?
2. Are the plant categories appropriate?
3. Should the linear relationship between application rate and residue level be changed?
4. Are the residue levels the same for all classes of chemicals?
5. Do plant morphological features influence residue levels?
6. How is residue decay over time related to plant category and/or chemical class?

MATERIALS AND METHODS

The Kenaga nomogram estimates residue levels (parts per million, based on fresh weight) present immediately following chemical application (day 0). Two analytical methods

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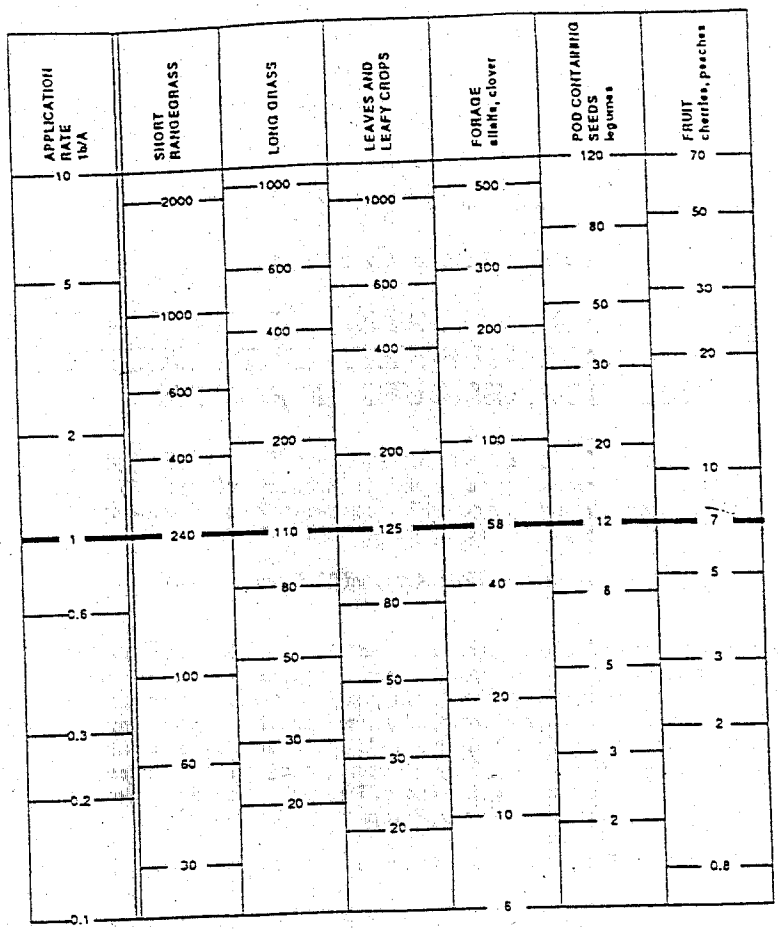

Fig. 1. The EPA food-chain (Kenaga) nomogram used to predict pesticide residues in ppm immediately following chemical application to different categories of plants and plant parts [3].

were conducted to evaluate the accuracy of the nomogram's day-0 estimates. The first was an examination of data plotted as residue level vs. application rate for the six different plant categories in the nomogram (Fig. 1). Twelve plots were prepared: two per category (days 0 and 1) for each of the six categories of plants and plant parts present in the Kenaga nomogram. Representative plots are shown in Figure 2. The diagonal line on each graph shows the dose–residue relationship predicated by the Kenaga nomogram. Data points above individual lines represent values reported in the literature that exceeded the upper limit values predicted by the Kenaga nomogram. Tabulation of the number of times data points exceeded the predicted values (Table 1) was used to evaluate the accuracy of the nomogram for each category of plants. Although the Kenaga nomogram deals only with day 0, we analyze both day-0 and day-1 data to gain the largest possible data set.

The second method of analyzing the accuracy of the nomogram's day-0 estimates was to process data from the UTAB database in the manner described by Hoerger and Kenaga [4], and then make direct comparisons with their results. All data were standardized to the same units (ppm plant residue per lb active ingredient applied pesticide per acre) by dividing the actual residue reported by the treatment rate used in the study. This is the same calculation used by Hoerger and Kenaga [4] to arrive at the RUD (residue from a unit dosage) values reported in their review. Only day-0 data were used for this analysis for a direct comparison with the nomogram.

The design of the Kenaga nomogram does not permit estimates of residue amounts beyond day 0 following chemical application. However, because it might be a worthwhile addition to the nomogram, we examined this relationship by preparing plots of plant residues (ppm) vs. time (d) following chemical application. The analyses were restricted to applications ranging from 0.5 to 1.5 lb/acre; such a range includes rates most commonly used under field conditions. Individual graphs were prepared. Rates of chemical disappearance were statistically compared to an exponential decay curve by major classes of pesticides and each of the plant categories in the nomogram.

All of the data used in this study were taken from the UTAB database [5,6] developed at the University of Oklahoma. UTAB contains information on the uptake/accumulation, translocation, biotransformation, and adhesion of both organic chemicals and heavy metals by vascular plants.

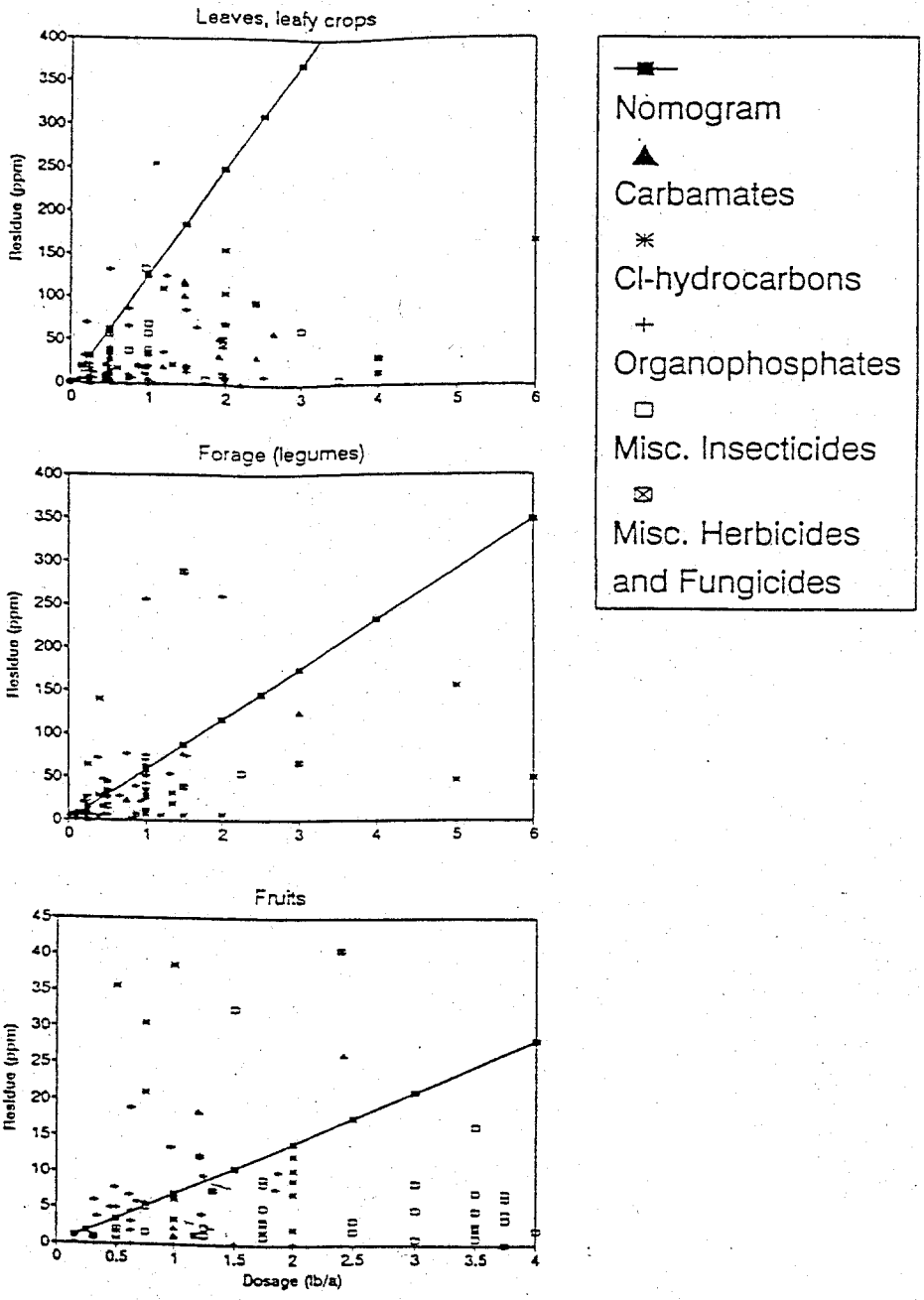

Fig. 2. Comparison of day-0 residue levels reported in the literature with those predicted by the Kenaga nomogram for three different plant categories. The diagonal line is the relationship between application rate and residue level as predicted by the Kenaga nomogram. Cl-hydrocarbons = chlorinated hydrocarbons.

The database has 42,000 individual records pertaining to over 1,000 different organic chemicals, 65% of which are pesticides. These data were compiled from the review of over 100 published papers. There are over 400 species of plants in UTAB, representing 95 plant families and all major crops.

For the purposes of this study, the information in UTAB was screened for experimental conditions and data expressions that were consistent with the data set used by Hoerger and Kenaga [4]. Only field studies reporting residue data as parts per million based on plant fresh weight were used. The data were divided into plant categories according to those used in the Kenaga nomogram. Some species of grasses could have been categorized as either short range grass or long grass. For example, fescue (*Festuca* sp.), which is grown as a pasture and hay crop, may be considered a short range grass in pastures and/or a long grass in hay fields. To resolve

Table 1. Number of times day-0 and day-1 residue values from UTAB exceeded residue amounts predicted by Kenaga nomogram

Plant type	Insecticides			Herbicides and fungicides			Totals		
	No. of residue values	E[a]	%	No. of residue values	E	%	No. of residue values	E	%
Short range grass									
Day 0	18 (7)[b]	0	0.0	0 (0)[b]	—	—	18 (7)[b]	0	0.0
Day 1	27 (8)	0	0.0	0 (0)	—	—	27 (8)	0	0.0
Long grass									
Day 0	44 (18)	2	4.5	2 (2)	0	0.0	46 (20)	2	4.3
Day 1	40 (14)	1	2.5	3 (2)	0	0.0	43 (16)	1	2.3
Leaves, leafy crops									
Day 0	139 (31)	5	3.6	13 (6)	0	0.0	152 (37)	5	3.3
Day 1	131 (36)	0	0.0	2 (2)	0	0.0	133 (38)	0	0.0
Forage (legumes)									
Day 0	90 (23)	19	21.3	6 (5)	2	33.3	96 (28)	21	22.1
Day 1	54 (20)	4	7.4	5 (2)	1	20.0	59 (22)	5	8.5
Pods/seeds (legumes)									
Day 0	25 (9)	1	4.0	1 (1)	1	100	26 (10)	2	7.7
Day 1	26 (11)	0	0	1 (1)	1	100	27 (12)	1	3.7
Fruit									
Day 0	104 (20)	20	19.2	4 (3)	1	25.0	108 (23)	21	19.4
Day 1	85 (18)	6	7.1	10 (3)	1	10.0	95 (21)	7	7.4
Totals									
Day 0	420	47	11.2	26	4	15.4	446	51	11.5
Day 1	363	11	3.0	21	3	14.3	384	14	3.6

[a]Residue values that exceed the amount predicted by the Kenaga nomogram.
[b]Pesticides represented.

this dilemma in our study, the short range grass category was restricted to grasses that are short (20 cm) when mature (e.g., buffalograss [*Buchloe dactyloides*] and blue grama [*Bouteloua gracilis*]), or used primarily as lawn and/or pasture grass (e.g., bermudagrass, *Cynodon dactylon*), and we ignored the aspect of their being range grasses. In keeping with the Kenaga nomogram, dicotyledonous plants were divided into two groups: forage (leguminous plants), and leaves and leafy crops (all other broad-leaved crops).

The total data set used in this evaluation of both day-0 residue values and residue decay through time was taken from 249 published papers whose data are encoded into UTAB [5]. This included information on 118 species of plants (mostly crops, including 27 grass species and 16 legume species), 121 different pesticides (85 insecticides, 27 herbicides, and 9 fungicides), and 17 classes of chemicals. The 17 examined classes of chemicals were aromatic acids, brominated hydrocarbons, carbamates, chlorinated hydrocarbons, chlorinated sulfites, formamidines, haloalkanoics, organophosphates, nitriles, nitrophenols, pyrethroids, pyridines, thiocarbamates, triazines, ureas, vinyl phosphates, and miscellaneous unclassified pesticides. In comparison to the data set used by Hoerger and Kenaga [4], our study involved six times more pesticides (121 vs. 21), two times more plant species (118 vs. 60), and 11 times more published papers (249 vs. 22).

RESULTS

Predicted residue values

Day-0 residues (pesticide levels on days 0 or 1 following application) were examined for 72 plant species and 78 chemicals. The number of residue values were similar for both day 0 (420) and day 1 (363). Most residue data pertained to leaves and leafy crops, legume foliage, and fruit. These data were examined by preparing 12 graphs, showing the relationship between application rate and residue level on either day 0 or day 1 for each of the six plant–nomogram categories. Examination of these graphs revealed major differences in the predictive accuracy of the nomogram. As an example, for leaves and leafy crops (Fig. 2) very few values exceeded those predicted by the nomogram, but forage (legume) and fruits (Fig. 2) had a large number of exceeding values. Table 1 gives an overview of the data points exceeding the predicted values for all six categories on both day 0 and day 1.

Plant categories

Analysis of the data pertaining to nomogram categories involving monocotyledon plants (grasses) (Table 1) showed that all of the short range-grass values were below those predicted by the nomogram. The long-grass category had three exceeding values: two on day 0 and one on day 1. These values involved chlorinated hydrocarbons no longer used in the United States.

A comparison of residue data reported on dicotyledons with data predicted by the nomogram showed that for leafy crop plants, 3.3% of the records on day 0 (Fig. 2) and none of the records on day 1 (Table 1) exceeded the nomogram predictions. In contrast, residue levels reported for forage plants showed a much greater discrepancy with those predicted by the nomogram. Twenty-one of the 96, or 22% of the residue values, exceeded the predicted values on day 0 (Fig. 2) and five of 59, or 8.5%, on day 1 (Table 1). These values involved

.5 chemicals representing five classes of compounds (Fig. 2) and six different species of plants.

The Kenaga nomogram has two separate categories for fruits: One covers legume pods and the other includes fruits of all other plants (Fig. 1). Our analysis showed exceeding values for both categories, but the general fruit category had a higher percentage. For legume pods, the frequencies of exceeding values over predicted values were 7.7 and 3.7% on days 0 and 1, respectively (Table 1), whereas the percentages for the other fruits were 19.4 and 7.4%. The 21 exceeding values associated with fruits on day 0 involved six different classes of compounds and 10 different chemicals: two chlorinated hydrocarbons, four organophosphates, one carbamate, one thiocarbamate, one aromatic acid, and one unclassified compound (Fig. 2). Closer examination of the fruit data exceeding on day 0 showed that fruits of woody plants such as apricot and peach had more exceeding values (15 of 62 or 24.2%) than those of herbaceous plants such as tomato and okra (6 of 46, or 13.0%).

The total number of exceeding values for all plant and organ categories was 51 on day 0 and 14 on day 1, representing 11.5 and 3.6%, respectively, of the total data (Table 1). These percentages are not exceptionally high, but they are noteworthy because they represent residue values exceeding the original data compiled by Hoerger and Kenaga [4], who contended in their review article that there was very little probability of residue levels exceeding the upper-limit values they reported; of special concern were the high percentages of exceeding values (22 and 19%) associated with forage and fruit, respectively. All exceeding values were examined further to determine if the majority could be attributed to a single cause such as application rate, particular pesticide, class of chemicals, anatomical feature, or taxonomic group.

Residue level/application rate

Examination of the 12 individual plots (application rate vs. plant residue) such as those shown in Figure 2 showed no correlation between high application rates and high numbers of exceeding values. Thus the linear relationship that the Kenaga nomogram has between application rate and residue amounts is consistent with our findings.

Residue level/chemical class

A list of exceeding values by pesticide and chemical class (Table 2) showed that no single pesticide or chemical class accounted for the majority of the high values and that most of the exceeding values involved pesticides that are currently used. There were occasions when all of the residue values for a particular pesticide exceeded the predicted value (chlorobenzilate, EPN, and SD-7438). There were only limited data records for these compounds; therefore, these high values accounted for a small proportion of the total exceeding data points. No single pesticide or class of chemicals provided a comprehensive explanation for the exceeding data.

Residue level/plant morphology

The distribution of exceeding values among different species and plant types was examined to determine if the high residue values correlated with any particular anatomical feature (surface texture, leaf shape, etc.) or taxonomic group

Table 2. Distribution by chemical of combined day-0 and day-1 residue values exceeding predictions of Kenaga nomogram

Chemical class pesticide	No. of residue values	E^a	%
Aromatic acids			
Chlorobenzilate	2	2	100.0
Carbamates			
Carbaryl	34	5	14.7
4 other chemicals	21	0	0.0
Chlorinated hydrocarbons			
DDD	3	1	33.3
DDT	59	8	13.6
Endrin	12	2	16.7
Telodrin	3	1	33.3
8 other chemicals	64	0	0.0
Haloalkanoics			
2,4-DB	7	2	28.6
4 other chemicals	9	0	0.0
Organophosphates			
Azinphosmethyl	15	2	13.3
Baytex	4	1	25.0
Bidrin	6	2	33.3
Demeton (Systox)	13	5	38.5
Dimethoate	53	2	3.8
EPN	3	3	100.0
Fenitrothion	8	2	25.0
Malathion	58	6	10.3
Parathion (ethyl and methyl)	95	7	7.4
Phosphamidon	32	1	3.1
Quinalphos	6	1	16.7
SD-7438	2	2	100.0
20 other chemicals	123	0	0.0
Pyridines			
Picloram	2	1	50.0
Thiocarbamates			
Maneb	12	4	33.3
Morestan	15	0	0.0
Miscellaneous unclassified			
Methomyl	14	1	7.1
Methoxychlor	63	4	6.3
8 other chemicals	27	0	0.0
7 other chemical classes[b]			
10 chemicals	65	0	0.0
Totals	830	65	7.8

[a]Residue values that exceeded amount predicted by the Kenaga nomogram.
[b]Brominated hydrocarbons, chlorinated sulfites, formamidines, nitriles, nitrophenols, triazines, and vinyl phosphates.

(Table 3). Although there were several examples of high residue levels on plants with pubescent (hairy) leaves or fruit, the number and magnitude of these exceeding values were approximately the same as those present on nonpubescent plants. Consideration of other anatomical features led to the same conclusion. However, examination of the plant list provided additional evidence that two of the nomogram categories (forage and fruits) had disproportionately high numbers of exceeding values in comparison to the other categories. Thirty-two percent (18 of 57) of the residue values for alfalfa exceeded the predicted 58-ppm value for forage crops. When compared to other species for which we had similar data (44 values for Chinese cabbage and 66 for corn), alfalfa exceeded the nomogram-predicted value 14 and 7 times more often than Chinese cabbage and corn, respectively. In addi-

Table 3. Distribution by plant category and species of combined day-0 and day-1 residue values that exceeded predictions of Kenaga nomogram

Plant category and species	No. of residue values	E^a	%
Short range grass			
Bermuda grass (*Cynodon dactylon*)	45	0	0.0
Total	45	0	
Long grass			
Corn (*Zea mays*)	66	3	4.5
7 other species	23	0	0.0
Total	89	3	
Leaves, leafy crops			
Cabbage, Chinese (*Brassia pekinansis*)	44	1	2.3
Cherry (*Prunus* sp.)	1	1	100.0
Cotton[b] (*Gossypium hirsutum*)	11	2	18.2
Spearmint (*Mentha* sp.)	2	1	50.0
34 other species	227	0	0.0
Total	285	5	
Forage (legumes)			
Alfalfa (*Medicago sativa*)	57	18	31.6
Bean, green (*Phaseolus vulgaris*)	9	1	11.1
Clover, red (*Trifolium praterse*)	16	1	6.2
Clover, white (*T. repens*)	12	2	16.7
Mesquite (*Prosopis juliflora*)	1	1	100.0
Pea (*Pisum sativum*)	18	3	16.7
5 other species	42	0	0.0
Total	155	26	
Legume pods			
Bean, green (*Phaseolus vulgaris*)	39	3	7.7
3 other species	14	0	0.0
Total	53	3	
Fruit			
Apple (*Malus* sp.)	6	1	16.7
Apricot[b] (*Prunus armeniaca*)	5	5	100.0
Eggplant (*Solanum melongena*)	7	3	42.8
Grape (*Vitis* sp.)	13	5	38.5
Lemon (*Citrus limon*)	7	2	28.6
Okra[b] (*Hibiscus esculentus*)	21	1	4.8
Olive (*Olea europea*)	2	2	100.0
Peach[b] (*P. persica*)	5	2	40.0
Pear (*Pyrus communis*)	8	1	12.5
Rape (*Brassica napus*)	4	4	100.0
Tomato (*Lycopersicon esculentum*)	14	2	14.3
13 other species	111	0	0.0
Total	203	28	
Totals	830	65	7.8

[a]Residue values that exceeded the amount predicted by the Kenaga nomogram.
[b]Plant leaves or fruits that are pubescent (hairy).

tion to alfalfa, five of the other 10 forage crops (legume species) had residue values in excess of predicted values. The same observation was made for fruits, for which 11 of the 24 types of fruit had higher than predicted residue levels. The large number of exceeding values and general distribution among several plants with the forage and fruit categories were not characteristic of the other categories and, therefore, suggested that the predictive value of the Kenaga nomogram for forage and fruits is not accurate.

Residue decay over time

Although the current Kenaga nomogram addresses only day-0 residues immediately following application, the persistence of residues on vegetation is perhaps another factor the nomogram should address. In this regard, a comparison of the numbers of exceeding values on days 0 and 1 (Table 1) showed a marked decrease on the second day, even though the numbers of data points were similar in most cases. A more in-depth assessment of pesticide persistence was conducted by examining residue-decay curves of pesticides administered at rates between 0.5 and 1.5 lb/acre. Nineteen plots of various combinations of plant categories and classes of pesticides were examined. Almost all of the data fit exponential decay curves with significance at a p value of 0.01. The exception was data for systemic pesticides applied as either granules or dust. For example, when either disulfoton or carbamates were provided to dicotyledons (plants from both the forage and the leafy crop categories) (Fig. 3), no apparent exponential decay occurred over the first 30 to 40 d following application. These lingering residues were, for the most part, below the day-0 levels predicted by the Kenaga nomogram.

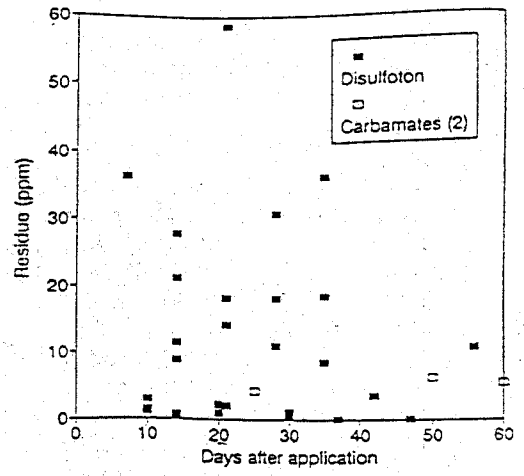

Fig. 3. Residue decay plot for selected systemic pesticides applied as granules or dust. Chemicals were applied in the dose range of 0.5 to 1.5 lb/acre. The two carbamate chemicals are aldicarb and carbofuran.

Further considerations

The Kenaga nomogram was evaluated further by analyzing data from the UTAB database in the same manner as that of Hoerger and Kenaga [4]. For this purpose, day-0 data were standardized as described in "Materials and Methods" so that all residue values were expressed as ppm plant residue/lb active ingredient applied pesticide/acre. The range and mean of values for each category were then compared to the predicted nomogram value (Table 4), which is the highest value reported by Hoerger and Kenaga [4] for each category in their 1972 survey. Our analysis of data from UTAB showed a broad range of residue values for each category, the upper limit of which exceeded the predicted nomogram value in each case, except for short range grass, consistent with the earlier discussion of exceeding values. Because of the importance that upper limit values play in the Kenaga nomogram, a brief description and citation are provided in Table 5 for

Table 4. Comparison of reported day-0 residue values with those predicted by Kenaga nomogram

Plant, organ category	No. of data records	Residue (ppm) following 1 lb a.i./acre application: Range Low	Range High	Mean	Predicted nomogram value
Short range grass	18 (1)[a] (7)[b]	15.3	194	84.8 (60.3)[c]	240
Long grass	46 (6) (20)	0.12	197	36.0 (40.6)	110
Leaves, leafy crops	152 (33) (37)	0.23	296	35.0 (45.0)	125
Forage (legumes)	96 (10) (28)	0.05	350	45.0 (56.7)	58
Pods and seeds (legumes)	26 (3) (10)	0.05	24.6	4.0 (5.9)	12
Fruit	108 (23) (23)	0	40.7	5.4 (9.8)	7
Woody	62 (13) (17)	0.003	40.7	6.7 (12.4)	7
Herbaceous	46 (10) (9)	0	16.9	3.6 (4.4)	7

[a]Number of species.
[b]Number of chemicals.
[c]SD.

each of the studies associated with the maximum values shown in Table 4. The differences between the high-range values identified in our study and the predicted nomogram values varied and were dependent on category. There was approximately a twofold difference between these values for long grass, leafy crops, and pods, but a sixfold difference occurred for both legumes and fruits. These same differences were also present when arithmetic means calculated by Hoerger and Kenaga [4] were compared to predicted nomogram values. When the individual nomogram values were divided by the respective mean values from our study, the resulting ratios were 2.8, 3.1, 3.6, and 3.0 for short range grass, long grass, leafy crops, and pods, respectively; whereas it was only 1.3 for both forage and fruits. These comparisons indicate that for forage and fruit plants the predictive values on the Kenaga nomogram are too low. This contention is further emphasized by observing that the mean value for forage plants (Table 4) is larger than that for leafy crops (45 vs. 35), but the nomogram values are reversed (58 vs. 125). The same type of relationship holds for fruits and pods. The mean value for fruits was 5.4 as compared to a 4.0 for pods, but the predictive values for the two are reversed, 7 for fruits and 12 for pods.

The accuracy of the plant groupings originally proposed by Hoerger and Kenaga and later adopted by EPA was further evaluated by a comparison between the mean values in our study for each of the plant and organ categories (Table 4). A major difference was observed between the mean values for short range grass (84.8) and long grass (36.0); this difference is consistent with the distinction between the two categories in the nomogram. In contrast, separation of dicotyledonous plants into leafy crops and forage legumes according to the nomogram was not strongly supported by our study because the mean values for these two groups were similar. The same was true for the pod and fruit categories. The nomogram makes a distinction between the two, but the mean values in our study were much closer than the standard deviation of either.

DISCUSSION

The EPA food-chain nomogram is a simple device used to predict maximum residue levels for any pesticide applied

Table 5. Upper-limit residue values reported in literature for plant and organ categories in Kenaga nomogram

Plant category	Residue value (ppm)	Plant species	Chemical	Research location	Date of study	Ref.
Short range grass	240[a]	Native grass	Tordon	Montana	1966	[7]
	(194)[b]	Bermuda grass	Dimethoate	Georgia	1961	[8]
Long grass	110	—	Malathion	—	—	[9]
	(197)	Corn	DDT	Iowa	1950	[10]
Leaves, leafy crops	125	Apple	EPN	Ohio	1950	[11]
	(296)	Cherry	Demeton	Washington	1954	[12]
Forage (legumes)	58	Alfalfa	Endosulfan	Ohio	1961	[13]
	(350)	Alfalfa	Endrin	California	1963	[14]
Pods and seeds	12	Green beans	Methoxychlor	Maryland	1956	[15]
	(24.6)	Green beans	Maneb	Ontario	1974	[16]
Fruit	7	Cherry	Endosulfan	California	1960	[13]
	(40.7)	Apricot	DDT	California	1949	[17]

[a]Reported in Hoerger and Kenaga [4].
[b]Identified in our search of the UTAB database.

at any rate to any plant grown in the United States. Considering the broad spectrum of plant-chemical combinations, as well as the multitude of diverse environmental (weather) conditions that prevail across the United States, it is appropriate to evaluate the nomogram's accuracy with data drawn from research studies of a broad spectrum of different plant, chemical, and environmental combinations. The UTAB database afforded us the opportunity to identify such a data set. Comparison of values in the UTAB data set to values predicted by the EPA nomogram has shown that the existing nomogram is, in general, accurate; however, there are some exceptions. The following proposed modifications should be considered.

The residue levels for each of the six categories in the current nomogram are based on the highest value reported for each category in the survey published by Hoerger and Kenaga [4]. The values set for four of these categories (short range grass, long grass, leafy crops, and pods) appear satisfactory, because we found very few occasions when values reported in the literature for these categories exceeded the nomogram predictions. In contrast, the residue levels predicted for the two remaining categories (forage crops and fruit) were often lower than those reported in the literature and should be adjusted. Predicted values could be elevated to match the highest reported values in the literature, the same philosophy used in creating the existing nomogram. An alternative would be to adjust the highest nomogram values with respect to the mean values calculated in our study. In respect to the latter suggestion, for those categories in which predictions were accurate (short range grass, long grass, leafy crops, and pods), a ratio of three was observed when the nomogram values were divided by mean values of the analyzed data. Even though there was no strong mathematical justification, if this threefold factor were used to adjust the current nomogram values for the forage and fruit categories, from 58 to 135 and from 7 to 15, respectively, then the number of exceeding values on day 0 would be reduced from 21 to 5 (22.1 to 5.2%) for forage crops and from 21 to 9 (19.4 to 8.3%) for fruit.

Adjustment of the nomogram as suggested in the previous paragraph warrants consideration of merging categories with similar predictive values. For example, as the new suggested value of 135 for forage crops is close to the existing value of 125 for leafy crops, it would be appropriate to combine the two into a broadleaf category and set the prediction value at 135. In a similar fashion, fruits (new value 15) and pods (old value 12) could be placed in a single fruit category set at 15. Our analyses indicated that the present separation of grasses into two categories is desirable. If our suggestions were implemented, the number of categories would be reduced from six to four with predictive values of 240, 110, 135, and 15 for short range grass, long grass, broadleaf plants, and fruits, respectively.

An additional minor change would be to remove the term *range* from the short-range-grass heading. Our rationale is that the term *short range grass* is confusing because all range grasses are not short, and numerous grasses not growing as a range grass are short (i.e., mowed or grazed cultivated pastures). Our analysis did show a major difference between the residue level of short vs. tall grasses, irrespective of where they grew; therefore, two grass categories should remain but the term *range* should be eliminated.

Analyses of the correlations between residue level and various parameters showed that the simplicity of the existing nomogram regarding uniform treatment of all classes of chemicals, the linear relationship between application rate and residue prediction, and a disregard for anatomical plant features (i.e., pubescent leaves) does not jeopardize accuracy. We did show that there was a greater persistence of some systemic pesticides applied as granules and powders, but the residue levels were so low in comparison to the day-0 levels that there was no strong justification for modifying the nomogram to include decay or accumulation of pesticide over time following application.

Our analyses indicate that with minor modifications (elevation of the predictive values for forage and fruit categories) the Kenaga nomogram provides accurate maximum residue predictions. Only 5% of values exceed those predicted by the nomogram. This conclusion is based on reported literature values, which should be tested with specially planned and conducted risk assessment research.

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LITERATURE REVIEW AND EVALUATION OF THE EPA FOOD-CHAIN (KENAGA) NOMOGRAM, AN INSTRUMENT FOR ESTIMATING PESTICIDE RESIDUES ON PLANTS

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Abstract—The Kenaga nomogram is a simple device that was developed by the U.S. Environmental Protection Agency (EPA) in the early 1980s and is currently used to predict the maximum potential pesticide residue levels in the food chain of wildlife before pesticide registration. To evaluate the accuracy of this nomogram, predicted levels were compared to levels reported in the literature. Data (obtained from the UTAB database developed by the University of Oklahoma) demonstrated that day-0 levels predicted by the nomogram were often exceeded. Data from the UTAB database exceeded the nomogram predictions by the following percentages listed by crop: short range grass, 0; leafy crops, 3; long grass, 4; pods/seeds, 8; fruits, 19; and forage (legumes), 22. Minor modification of the nomogram is recommended. Recommended modifications would result in an elevation of the predicted residue levels for fruits and forage (legume) crops.

Keywords—Food chain Nomogram Pesticides Plant residue UTAB database

INTRODUCTION

Ecological risk assessment of the hazard posed by agrochemicals to wildlife requires consideration of both the toxicity of chemicals to wildlife and the exposure that birds and other animals receive in natural habitats [1,2]. The U.S. Environmental Protection Agency (EPA) initially estimates the ecological risk associated with pesticides by using a quotient method that divides the estimated level of environmental exposure by the concentration of a chemical required to elicit a biological response (usually lab data) [1]. Quotient values approaching or exceeding 1.0 indicate that a given chemical is more likely to have an adverse effect on wildlife in the environment.

Exposure levels (i.e., the quotient's numerator) are based in part on estimates of food-chain contamination often found through the use of a simple nomogram (Fig. 1) compiled by the EPA in the early 1980s. The nomogram [3] has been nicknamed the Kenaga nomogram by the EPA in recognition of the source of the data used to compile it [4]. The Kenaga nomogram is used to predict maximum residue level present on day 0 following different application rates of a chemical to one of six different categories of plants or plant parts.

The three basic features of the Kenaga nomogram—categories of plants and plant parts, maximum predicted residue levels, and linear dose–residue relationship—are drawn from a review article published by Hoerger and Kenaga in 1972 [4]. In preparing their review article, the authors reported they considered several hundred publications, but only included illustrative data in their review from the 22 papers they found with the highest levels of pesticide residues from spray application. Thus, Hoerger and Kenaga purposefully emphasized the most rigorous situations requiring toxicological evaluation of which they were aware at that time, and contended that it was highly unlikely for residue levels to exist above the upper-limit values reported in their publication.

The data taken from the Hoerger–Kenaga review and used by the EPA to develop the Kenaga nomogram pertain to 36 crops and 27 pesticides. However, 10 of the 27 pesticides considered by Hoerger and Kenaga in 1972 are now either banned or no longer registered in the United States (e.g., DDT, dieldrin, endrin, and aldrin). Also, many pesticides have been introduced. In light of these developments, there is a need to reexamine and possibly update the Kenaga nomogram.

This study reexamines the Kenaga nomogram using voluminous information compiled at the University of Oklahoma in the UTAB database [5,6]. Database information regarding both crops and pesticides has been used in this reexamination, which was guided by six questions:

1. Are the maximum predicted residue values correct?
2. Are the plant categories appropriate?
3. Should the linear relationship between application rate and residue level be changed?
4. Are the residue levels the same for all classes of chemicals?
5. Do plant morphological features influence residue levels?
6. How is residue decay over time related to plant category and/or chemical class?

MATERIALS AND METHODS

The Kenaga nomogram estimates residue levels (parts per million, based on fresh weight) present immediately following chemical application (day 0). Two analytical methods

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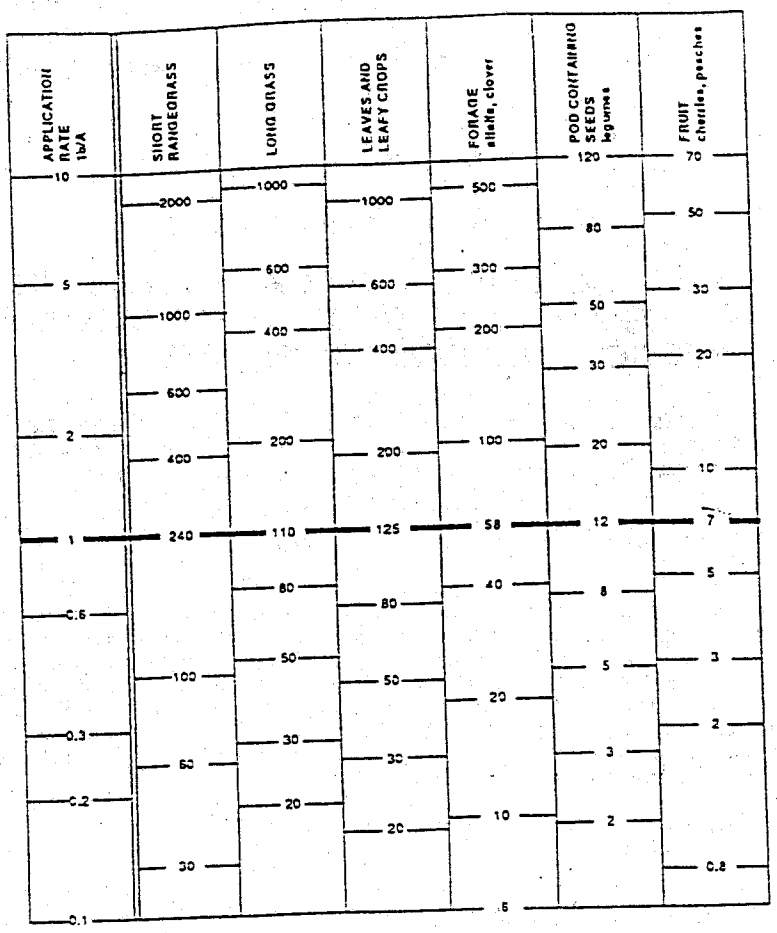

Fig. 1. The EPA food-chain (Kenaga) nomogram used to predict pesticide residues in ppm immediately following chemical application to different categories of plants and plant parts [3].

were conducted to evaluate the accuracy of the nomogram's day-0 estimates. The first was an examination of data plotted as residue level vs. application rate for the six different plant categories in the nomogram (Fig. 1). Twelve plots were prepared: two per category (days 0 and 1) for each of the six categories of plants and plant parts present in the Kenaga nomogram. Representative plots are shown in Figure 2. The diagonal line on each graph shows the dose–residue relationship predicated by the Kenaga nomogram. Data points above individual lines represent values reported in the literature that exceeded the upper limit values predicted by the Kenaga nomogram. Tabulation of the number of times data points exceeded the predicted values (Table 1) was used to evaluate the accuracy of the nomogram for each category of plants. Although the Kenaga nomogram deals only with day 0, we analyze both day-0 and day-1 data to gain the largest possible data set.

The second method of analyzing the accuracy of the nomogram's day-0 estimates was to process data from the UTAB database in the manner described by Hoerger and Kenaga [4], and then make direct comparisons with their results. All data were standardized to the same units (ppm plant residue per lb active ingredient applied pesticide per acre) by dividing the actual residue reported by the treatment rate used in the study. This is the same calculation used by Hoerger and Kenaga [4] to arrive at the RUD (residue from a unit dosage) values reported in their review. Only day-0 data were used for this analysis for a direct comparison with the nomogram.

The design of the Kenaga nomogram does not permit estimates of residue amounts beyond day 0 following chemical application. However, because it might be a worthwhile addition to the nomogram, we examined this relationship by preparing plots of plant residues (ppm) vs. time (d) following chemical application. The analyses were restricted to applications ranging from 0.5 to 1.5 lb/acre; such a range includes rates most commonly used under field conditions. Individual graphs were prepared. Rates of chemical disappearance were statistically compared to an exponential decay curve by major classes of pesticides and each of the plant categories in the nomogram.

All of the data used in this study were taken from the UTAB database [5,6] developed at the University of Oklahoma. UTAB contains information on the uptake/accumulation, translocation, biotransformation, and adhesion of both organic chemicals and heavy metals by vascular plants.

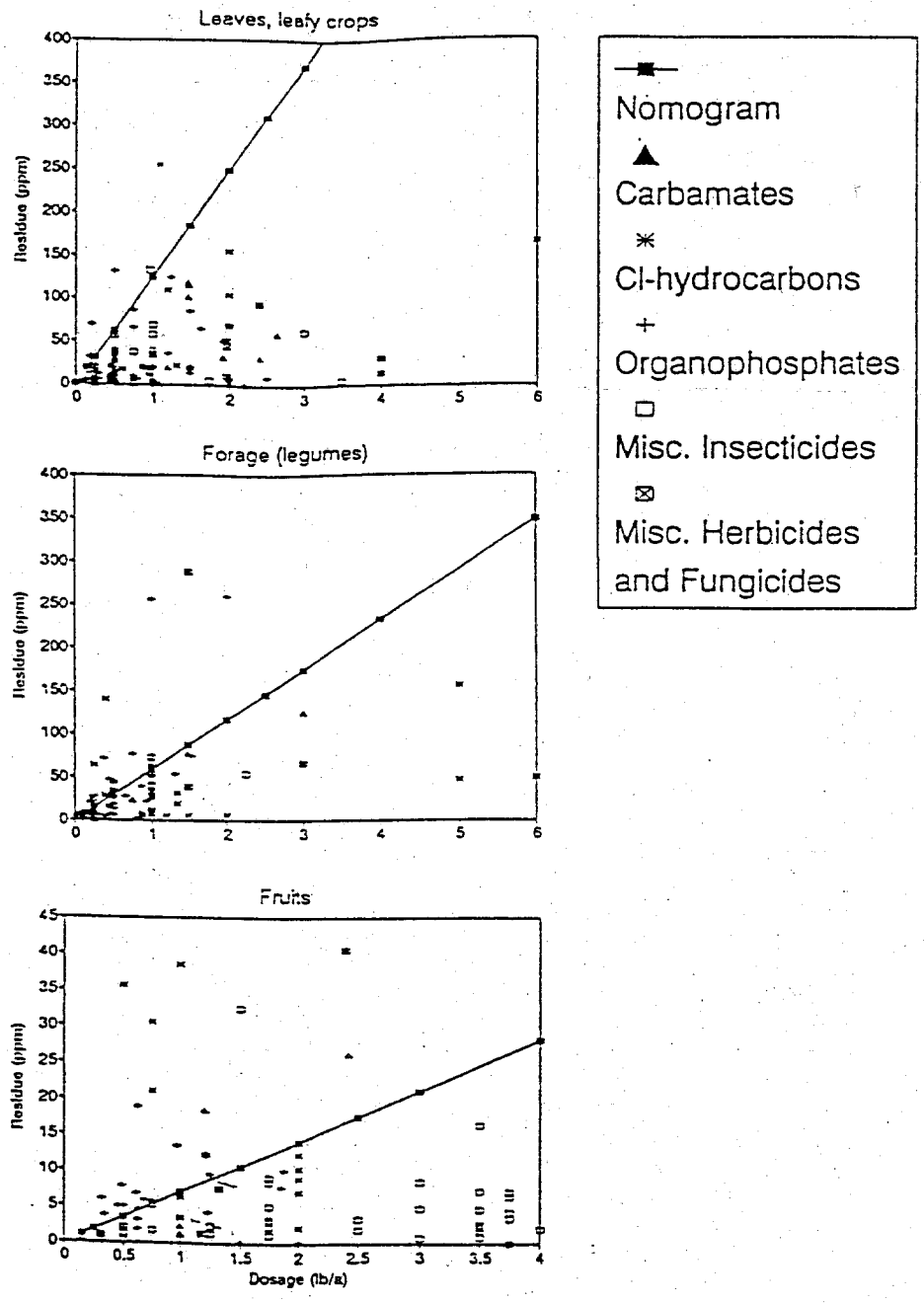

Fig. 2. Comparison of day-0 residue levels reported in the literature with those predicted by the Kenaga nomogram for three different plant categories. The diagonal line is the relationship between application rate and residue level as predicted by the Kenaga nomogram. Cl-hydrocarbons = chlorinated hydrocarbons.

The database has 42,000 individual records pertaining to over 1,000 different organic chemicals, 65% of which are pesticides. These data were compiled from the review of over 100 published papers. There are over 400 species of plants in UTAB, representing 95 plant families and all major crops.

For the purposes of this study, the information in UTAB was screened for experimental conditions and data expressions that were consistent with the data set used by Hoerger and Kenaga [4]. Only field studies reporting residue data as parts per million based on plant fresh weight were used. The data were divided into plant categories according to those used in the Kenaga nomogram. Some species of grasses could have been categorized as either short range grass or long grass. For example, fescue (*Festuca* sp.), which is grown as a pasture and hay crop, may be considered a short range grass in pastures and/or a long grass in hay fields. To resolve

Table 1. Number of times day-0 and day-1 residue values from UTAB exceeded residue amounts predicted by Kenaga nomogram

Plant type	Insecticides			Herbicides and fungicides			Totals		
	No. of residue values	E[a]	%	No. of residue values	E	%	No. of residue values	E	%
Short range grass									
Day 0	18 (7)[b]	0	0.0	0 (0)[b]	—	—	18 (7)[b]	0	0.0
Day 1	27 (8)	0	0.0	0 (0)	—	—	27 (8)	0	0.0
Long grass									
Day 0	44 (18)	2	4.5	2 (2)	0	0.0	46 (20)	2	4.3
Day 1	40 (14)	1	2.5	3 (2)	0	0.0	43 (16)	1	2.3
Leaves, leafy crops									
Day 0	139 (31)	5	3.6	13 (6)	0	0.0	152 (37)	5	3.3
Day 1	131 (36)	0	0.0	2 (2)	0	0.0	133 (38)	0	0.0
Forage (legumes)									
Day 0	90 (23)	19	21.3	6 (5)	2	33.3	96 (28)	21	22.1
Day 1	54 (20)	4	7.4	5 (2)	1	20.0	59 (22)	5	8.5
Pods/seeds (legumes)									
Day 0	25 (9)	1	4.0	1 (1)	1	100	26 (10)	2	7.7
Day 1	26 (11)	0	0	1 (1)	1	100	27 (12)	1	3.7
Fruit									
Day 0	104 (20)	20	19.2	4 (3)	1	25.0	108 (23)	21	19.4
Day 1	85 (18)	6	7.1	10 (3)	1	10.0	95 (21)	7	7.4
Totals									
Day 0	420	47	11.2	26	4	15.4	446	51	11.5
Day 1	363	11	3.0	21	3	14.3	384	14	3.6

[a]Residue values that exceed the amount predicted by the Kenaga nomogram.
[b]Pesticides represented.

this dilemma in our study, the short range grass category was restricted to grasses that are short (20 cm) when mature (e.g., buffalograss [*Buchloe dactyloides*] and blue grama [*Bouteloua gracilis*]), or used primarily as lawn and/or pasture grass (e.g., bermudagrass, *Cynodon dactylon*), and we ignored the aspect of their being range grasses. In keeping with the Kenaga nomogram, dicotyledonous plants were divided into two groups: forage (leguminous plants), and leaves and leafy crops (all other broad-leaved crops).

The total data set used in this evaluation of both day-0 residue values and residue decay through time was taken from 249 published papers whose data are encoded into UTAB [5]. This included information on 118 species of plants (mostly crops, including 27 grass species and 16 legume species), 121 different pesticides (85 insecticides, 27 herbicides, and 9 fungicides), and 17 classes of chemicals. The 17 examined classes of chemicals were aromatic acids, brominated hydrocarbons, carbamates, chlorinated hydrocarbons, chlorinated sulfites, formamidines, haloalkanoics, organophosphates, nitriles, nitrophenols, pyrethroids, pyridines, thiocarbamates, triazines, ureas, vinyl phosphates, and miscellaneous unclassified pesticides. In comparison to the data set used by Hoerger and Kenaga [4], our study involved six times more pesticides (121 vs. 21), two times more plant species (118 vs. 60), and 11 times more published papers (249 vs. 22).

RESULTS

Predicted residue values

Day-0 residues (pesticide levels on days 0 or 1 following application) were examined for 72 plant species and 78 chemicals. The number of residue values were similar for both day 0 (420) and day 1 (363). Most residue data pertained to leaves and leafy crops, legume foliage, and fruit. These data were examined by preparing 12 graphs, showing the relationship between application rate and residue level on either day 0 or day 1 for each of the six plant–nomogram categories. Examination of these graphs revealed major differences in the predictive accuracy of the nomogram. As an example, for leaves and leafy crops (Fig. 2) very few values exceeded those predicted by the nomogram, but forage (legume) and fruits (Fig. 2) had a large number of exceeding values. Table 1 gives an overview of the data points exceeding the predicted values for all six categories on both day 0 and day 1.

Plant categories

Analysis of the data pertaining to nomogram categories involving monocotyledon plants (grasses) (Table 1) showed that all of the short range-grass values were below those predicted by the nomogram. The long-grass category had three exceeding values: two on day 0 and one on day 1. These values involved chlorinated hydrocarbons no longer used in the United States.

A comparison of residue data reported on dicotyledons with data predicted by the nomogram showed that for leafy crop plants, 3.3% of the records on day 0 (Fig. 2) and none of the records on day 1 (Table 1) exceeded the nomogram predictions. In contrast, residue levels reported for forage plants showed a much greater discrepancy with those predicted by the nomogram. Twenty-one of the 96, or 22% of the residue values, exceeded the predicted values on day 0 (Fig. 2) and five of 59, or 8.5%, on day 1 (Table 1). These values involved

.5 chemicals representing five classes of compounds (Fig. 2) and six different species of plants.

The Kenaga nomogram has two separate categories for fruits: One covers legume pods and the other includes fruits of all other plants (Fig. 1). Our analysis showed exceeding values for both categories, but the general fruit category had a higher percentage. For legume pods, the frequencies of exceeding values over predicted values were 7.7 and 3.7% on days 0 and 1, respectively (Table 1), whereas the percentages for the other fruits were 19.4 and 7.4%. The 21 exceeding values associated with fruits on day 0 involved six different classes of compounds and 10 different chemicals: two chlorinated hydrocarbons, four organophosphates, one carbamate, one thiocarbamate, one aromatic acid, and one unclassified compound (Fig. 2). Closer examination of the fruit data exceeding on day 0 showed that fruits of woody plants such as apricot and peach had more exceeding values (15 of 62 or 24.2%) than those of herbaceous plants such as tomato and okra (6 of 46, or 13.0%).

The total number of exceeding values for all plant and organ categories was 51 on day 0 and 14 on day 1, representing 11.5 and 3.6%, respectively, of the total data (Table 1). These percentages are not exceptionally high, but they are noteworthy because they represent residue values exceeding the original data compiled by Hoerger and Kenaga [4], who contended in their review article that there was very little probability of residue levels exceeding the upper-limit values they reported; of special concern were the high percentages of exceeding values (22 and 19%) associated with forage and fruit, respectively. All exceeding values were examined further to determine if the majority could be attributed to a single cause such as application rate, particular pesticide, class of chemicals, anatomical feature, or taxonomic group.

Residue level/application rate

Examination of the 12 individual plots (application rate vs. plant residue) such as those shown in Figure 2 showed no correlation between high application rates and high numbers of exceeding values. Thus the linear relationship that the Kenaga nomogram has between application rate and residue amounts is consistent with our findings.

Residue level/chemical class

A list of exceeding values by pesticide and chemical class (Table 2) showed that no single pesticide or chemical class accounted for the majority of the high values and that most of the exceeding values involved pesticides that are currently used. There were occasions when all of the residue values for a particular pesticide exceeded the predicted value (chlorobenzilate, EPN, and SD-7438). There were only limited data records for these compounds; therefore, these high values accounted for a small proportion of the total exceeding data points. No single pesticide or class of chemicals provided a comprehensive explanation for the exceeding data.

Residue level/plant morphology

The distribution of exceeding values among different species and plant types was examined to determine if the high residue values correlated with any particular anatomical feature (surface texture, leaf shape, etc.) or taxonomic group

Table 2. Distribution by chemical of combined day-0 and day-1 residue values exceeding predictions of Kenaga nomogram

Chemical class pesticide	No. of residue values	E[a]	%
Aromatic acids			
Chlorobenzilate	2	2	100.0
Carbamates			
Carbaryl	34	5	14.7
4 other chemicals	21	0	0.0
Chlorinated hydrocarbons			
DDD	3	1	33.3
DDT	59	8	13.6
Endrin	12	2	16.7
Telodrin	3	1	33.3
8 other chemicals	64	0	0.0
Haloalkanoics			
2,4-DB	7	2	28.6
4 other chemicals	9	0	0.0
Organophosphates			
Azinphosmethyl	15	2	13.3
Baytex	4	1	25.0
Bidrin	6	2	33.3
Demeton (Systox)	13	5	38.5
Dimethoate	53	2	3.8
EPN	3	3	100.0
Fenitrothion	8	2	25.0
Malathion	58	6	10.3
Parathion (ethyl and methyl)	95	7	7.4
Phosphamidon	32	1	3.1
Quinalphos	6	1	16.7
SD-7438	2	2	100.0
20 other chemicals	123	0	0.0
Pyridines			
Picloram	2	1	50.0
Thiocarbamates			
Maneb	12	4	33.3
Morestan	15	0	0.0
Miscellaneous unclassified			
Methomyl	14	1	7.1
Methoxychlor	63	4	6.3
8 other chemicals	27	0	0.0
7 other chemical classes[b]			
10 chemicals	65	0	0.0
Totals	830	65	7.8

[a]Residue values that exceeded amount predicted by the Kenaga nomogram.
[b]Brominated hydrocarbons, chlorinated sulfites, formamidines, nitriles, nitrophenols, triazines, and vinyl phosphates.

(Table 3). Although there were several examples of high residue levels on plants with pubescent (hairy) leaves or fruit, the number and magnitude of these exceeding values were approximately the same as those present on nonpubescent plants. Consideration of other anatomical features led to the same conclusion. However, examination of the plant list provided additional evidence that two of the nomogram categories (forage and fruits) had disproportionately high numbers of exceeding values in comparison to the other categories. Thirty-two percent (18 of 57) of the residue values for alfalfa exceeded the predicted 58-ppm value for forage crops. When compared to other species for which we had similar data (44 values for Chinese cabbage and 66 for corn), alfalfa exceeded the nomogram-predicted value 14 and 7 times more often than Chinese cabbage and corn, respectively. In addi-

Table 3. Distribution by plant category and species of combined day-0 and day-1 residue values that exceeded predictions of Kenaga nomogram

Plant category and species	No. of residue values	E^a	%
Short range grass			
Bermuda grass (*Cynodon dactylon*)	45	0	0.0
Total	45	0	
Long grass			
Corn (*Zea mays*)	66	3	4.5
7 other species	23	0	0.0
Total	89	3	
Leaves, leafy crops			
Cabbage, Chinese (*Brassia pekinansis*)	44	1	2.3
Cherry (*Prunus* sp.)	1	1	100.0
Cotton[b] (*Gossypium hirsutum*)	11	2	18.2
Spearmint (*Mentha* sp.)	2	1	50.0
34 other species	227	0	0.0
Total	285	5	
Forage (legumes)			
Alfalfa (*Medicago sativa*)	57	18	31.6
Bean, green (*Phaseolus vulgaris*)	9	1	11.1
Clover, red (*Trifolium praterse*)	16	1	6.2
Clover, white (*T. repens*)	12	2	16.7
Mesquite (*Prosopis juliflora*)	1	1	100.0
Pea (*Pisum sativum*)	18	3	16.7
5 other species	42	0	0.0
Total	155	26	
Legume pods			
Bean, green (*Phaseolus vulgaris*)	39	3	7.7
3 other species	14	0	0.0
Total	53	3	
Fruit			
Apple (*Malus* sp.)	6	1	16.7
Apricot[b] (*Prunus armeniaca*)	5	5	100.0
Eggplant (*Solanum melongena*)	7	3	42.8
Grape (*Vitis* sp.)	13	5	38.5
Lemon (*Citrus limon*)	7	2	28.6
Okra[b] (*Hibiscus esculentus*)	21	1	4.8
Olive (*Olea europea*)	2	2	100.0
Peach[b] (*P. persica*)	5	2	40.0
Pear (*Pyrus communis*)	8	1	12.5
Rape (*Brassica napus*)	4	4	100.0
Tomato (*Lycopersicon esculentum*)	14	2	14.3
13 other species	111	0	0.0
Total	203	28	
Totals	830	65	7.8

[a]Residue values that exceeded the amount predicted by the Kenaga nomogram.
[b]Plant leaves or fruits that are pubescent (hairy).

tion to alfalfa, five of the other 10 forage crops (legume species) had residue values in excess of predicted values. The same observation was made for fruits, for which 11 of the 24 types of fruit had higher than predicted residue levels. The large number of exceeding values and general distribution among several plants with the forage and fruit categories were not characteristic of the other categories and, therefore, suggested that the predictive value of the Kenaga nomogram for forage and fruits is not accurate.

Residue decay over time

Although the current Kenaga nomogram addresses only day-0 residues immediately following application, the persistence of residues on vegetation is perhaps another factor the nomogram should address. In this regard, a comparison of the numbers of exceeding values on days 0 and 1 (Table 1) showed a marked decrease on the second day, even though the numbers of data points were similar in most cases. A more in-depth assessment of pesticide persistence was conducted by examining residue-decay curves of pesticides administered at rates between 0.5 and 1.5 lb/acre. Nineteen plots of various combinations of plant categories and classes of pesticides were examined. Almost all of the data fit exponential decay curves with significance at a p value of 0.01. The exception was data for systemic pesticides applied as either granules or dust. For example, when either disulfoton or carbamates were provided to dicotyledons (plants from both the forage and the leafy crop categories) (Fig. 3), no apparent exponential decay occurred over the first 30 to 40 d following application. These lingering residues were, for the most part, below the day-0 levels predicted by the Kenaga nomogram.

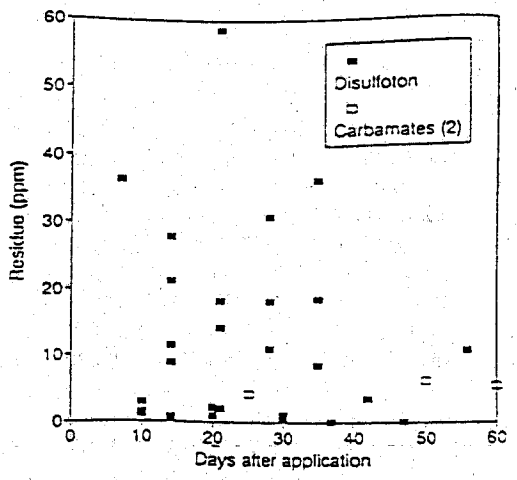

Fig. 3. Residue decay plot for selected systemic pesticides applied as granules or dust. Chemicals were applied in the dose range of 0.5 to 1.5 lb/acre. The two carbamate chemicals are aldicarb and carbofuran.

Further considerations

The Kenaga nomogram was evaluated further by analyzing data from the UTAB database in the same manner as that of Hoerger and Kenaga [4]. For this purpose, day-0 data were standardized as described in "Materials and Methods" so that all residue values were expressed as ppm plant residue/lb active ingredient applied pesticide/acre. The range and mean of values for each category were then compared to the predicted nomogram value (Table 4), which is the highest value reported by Hoerger and Kenaga [4] for each category in their 1972 survey. Our analysis of data from UTAB showed a broad range of residue values for each category, the upper limit of which exceeded the predicted nomogram value in each case, except for short range grass, consistent with the earlier discussion of exceeding values. Because of the importance that upper limit values play in the Kenaga nomogram, a brief description and citation are provided in Table 5 for

Table 4. Comparison of reported day-0 residue values with those predicted by Kenaga nomogram

Plant, organ category	No. of data records	Residue (ppm) following 1 lb a.i./acre application: Range Low	Range High	Mean	Predicted nomogram value
Short range grass	18 (1)[a] (7)[b]	15.3	194	84.8 (60.3)[c]	240
Long grass	46 (6) (20)	0.12	197	36.0 (40.6)	110
Leaves, leafy crops	152 (33) (37)	0.23	296	35.0 (45.0)	125
Forage (legumes)	96 (10) (28)	0.05	350	45.0 (56.7)	58
Pods and seeds (legumes)	26 (3) (10)	0.05	24.6	4.0 (5.9)	12
Fruit	108 (23) (23)	0	40.7	5.4 (9.8)	7
Woody	62 (13) (17)	0.003	40.7	6.7 (12.4)	7
Herbaceous	46 (10) (9)	0	16.9	3.6 (4.4)	7

[a]Number of species.
[b]Number of chemicals.
[c]SD.

each of the studies associated with the maximum values shown in Table 4. The differences between the high-range values identified in our study and the predicted nomogram values varied and were dependent on category. There was approximately a twofold difference between these values for long grass, leafy crops, and pods, but a sixfold difference occurred for both legumes and fruits. These same differences were also present when arithmetic means calculated by Hoerger and Kenaga [4] were compared to predicted nomogram values. When the individual nomogram values were divided by the respective mean values from our study, the resulting ratios were 2.8, 3.1, 3.6, and 3.0 for short range grass, long grass, leafy crops, and pods, respectively; whereas it was only 1.3 for both forage and fruits. These comparisons indicate that for forage and fruit plants the predictive values on the Kenaga nomogram are too low. This contention is further emphasized by observing that the mean value for forage plants (Table 4) is larger than that for leafy crops (45 vs. 35), but the nomogram values are reversed (58 vs. 125). The same type of relationship holds for fruits and pods. The mean value for fruits was 5.4 as compared to a 4.0 for pods, but the predictive values for the two are reversed, 7 for fruits and 12 for pods.

The accuracy of the plant groupings originally proposed by Hoerger and Kenaga and later adopted by EPA was further evaluated by a comparison between the mean values in our study for each of the plant and organ categories (Table 4). A major difference was observed between the mean values for short range grass (84.8) and long grass (36.0); this difference is consistent with the distinction between the two categories in the nomogram. In contrast, separation of dicotyledonous plants into leafy crops and forage legumes according to the nomogram was not strongly supported by our study because the mean values for these two groups were similar. The same was true for the pod and fruit categories. The nomogram makes a distinction between the two, but the mean values in our study were much closer than the standard deviation of either.

DISCUSSION

The EPA food-chain nomogram is a simple device used to predict maximum residue levels for any pesticide applied

Table 5. Upper-limit residue values reported in literature for plant and organ categories in Kenaga nomogram

Plant category	Residue value (ppm)	Plant species	Chemical	Research location	Date of study	Ref.
Short range grass	240[a]	Native grass	Tordon	Montana	1966	[7]
	(194)[b]	Bermuda grass	Dimethoate	Georgia	1961	[8]
Long grass	110	—	Malathion	—	—	[9]
	(197)	Corn	DDT	Iowa	1950	[10]
Leaves, leafy crops	125	Apple	EPN	Ohio	1950	[11]
	(296)	Cherry	Demeton	Washington	1954	[12]
Forage (legumes)	58	Alfalfa	Endosulfan	Ohio	1961	[13]
	(350)	Alfalfa	Endrin	California	1963	[14]
Pods and seeds	12	Green beans	Methoxychlor	Maryland	1956	[15]
	(24.6)	Green beans	Maneb	Ontario	1974	[16]
Fruit	7	Cherry	Endosulfan	California	1960	[13]
	(40.7)	Apricot	DDT	California	1949	[17]

[a]Reported in Hoerger and Kenaga [4].
[b]Identified in our search of the UTAB database.

at any rate to any plant grown in the United States. Considering the broad spectrum of plant–chemical combinations, as well as the multitude of diverse environmental (weather) conditions that prevail across the United States, it is appropriate to evaluate the nomogram's accuracy with data drawn from research studies of a broad spectrum of different plant, chemical, and environmental combinations. The UTAB database afforded us the opportunity to identify such a data set. Comparison of values in the UTAB data set to values predicted by the EPA nomogram has shown that the existing nomogram is, in general, accurate; however, there are some exceptions. The following proposed modifications should be considered.

The residue levels for each of the six categories in the current nomogram are based on the highest value reported for each category in the survey published by Hoerger and Kenaga [4]. The values set for four of these categories (short range grass, long grass, leafy crops, and pods) appear satisfactory, because we found very few occasions when values reported in the literature for these categories exceeded the nomogram predictions. In contrast, the residue levels predicted for the two remaining categories (forage crops and fruit) were often lower than those reported in the literature and should be adjusted. Predicted values could be elevated to match the highest reported values in the literature, the same philosophy used in creating the existing nomogram. An alternative would be to adjust the highest nomogram values with respect to the mean values calculated in our study. In respect to the latter suggestion, for those categories in which predictions were accurate (short range grass, long grass, leafy crops, and pods), a ratio of three was observed when the nomogram values were divided by mean values of the analyzed data. Even though there was no strong mathematical justification, if this threefold factor were used to adjust the current nomogram values for the forage and fruit categories, from 58 to 135 and from 7 to 15, respectively, then the number of exceeding values on day 0 would be reduced from 21 to 5 (22.1 to 5.2%) for forage crops and from 21 to 9 (19.4 to 8.3%) for fruit.

Adjustment of the nomogram as suggested in the previous paragraph warrants consideration of merging categories with similar predictive values. For example, as the new suggested value of 135 for forage crops is close to the existing value of 125 for leafy crops, it would be appropriate to combine the two into a broadleaf category and set the prediction value at 135. In a similar fashion, fruits (new value 15) and pods (old value 12) could be placed in a single fruit category set at 15. Our analyses indicated that the present separation of grasses into two categories is desirable. If our suggestions were implemented, the number of categories would be reduced from six to four with predictive values of 240, 110, 135, and 15 for short range grass, long grass, broadleaf plants, and fruits, respectively.

An additional minor change would be to remove the term *range* from the short-range-grass heading. Our rationale is that the term *short range grass* is confusing because all range grasses are not short, and numerous grasses not growing as a range grass are short (i.e., mowed or grazed cultivated pastures). Our analysis did show a major difference between the residue level of short vs. tall grasses, irrespective of where they grew; therefore, two grass categories should remain but the term *range* should be eliminated.

Analyses of the correlations between residue level and various parameters showed that the simplicity of the existing nomogram regarding uniform treatment of all classes of chemicals, the linear relationship between application rate and residue prediction, and a disregard for anatomical plant features (i.e., pubescent leaves) does not jeopardize accuracy. We did show that there was a greater persistence of some systemic pesticides applied as granules and powders, but the residue levels were so low in comparison to the day-0 levels that there was no strong justification for modifying the nomogram to include decay or accumulation of pesticide over time following application.

Our analyses indicate that with minor modifications (elevation of the predictive values for forage and fruit categories) the Kenaga nomogram provides accurate maximum residue predictions. Only 5% of values exceed those predicted by the nomogram. This conclusion is based on reported literature values, which should be tested with specially planned and conducted risk assessment research.

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